On the primordial helium content: CMB and stellar constraints

G. Bono[1], A. Balbi[2], S. Cassisi[3], N. Vittorio[2], and R. Buonanno[1,2],
1. Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monte Porzio Catone, Italy;
bono@mporzio.astro.it; buonanno@mporzio.astro.it
2. Dipartimento di Fisica, Università Tor Vergata, and INFN, Sezione di Roma II,
Via della Ricerca Scientifica 1, 00133 Roma, Italy;
balbi@roma2.infn.it; Nicola.Vittorio@roma2.infn.it
3. Osservatorio Astronomico di Collurania, via M. Maggini, 64100 Teramo;
cassisi@te.astro.it

ABSTRACT

We present the results of a joint investigation aimed at constraining the primordial He content (Y_P) on the basis of both the Cosmic Microwave Background (CMB) anisotropy and two stellar observables, namely the tip of the Red Giant Branch (TRGB) and the luminosity of the Zero Age Horizontal Branch (ZAHB). Current baryon density estimates based on CMB measurements cover a wide range values $0.009 \lesssim \Omega_b h^2 \lesssim 0.045$, that according to Big Bang Nucleosynthesis (BBN) models would imply $0.24 \lesssim Y_P \lesssim 0.26$. We constructed several sets of evolutionary tracks and HB models by adopting $Y_P = 0.26$ and several metal contents. The comparison between theory and observations suggests that ZAHB magnitudes based on He-enhanced models are 1.5σ brighter than the empirical ones. The same outcome applies for the TRGB bolometric magnitudes. This finding somewhat supports a Y_P abundance close to the canonical 0.23-0.24 value. More quantitative constraints on this parameter are hampered by the fact that the CMB pattern shows a sizable dependence on both Y_P and the baryon density only at small angular scales, i.e. at high l in the power spectrum ($l \gtrsim 100$). However, this region of the power spectrum could be still affected by deceptive systematic uncertainties.

Finally, we suggest to use the *UV-upturn* to estimate the He content on Gpc scales. In fact, we find that a strong increase in Y_P causes in metal-poor, hot HB structures a decrease in the UV emission.

Subject headings: cosmic microwave background – cosmology: theory – stars: abundances – stars: evolution – stars: horizontal branch

1. Introduction

The comparison between chemical abundances of deuterium, helium, and lithium predicted by BBN models with current empirical estimates is one of the most viable method to constrain the physical mechanisms and the cosmology which governed the nucleosynthesis of primordial abundances (Olive, Steigman, & Walker 2000).

As far as the primordial He content is concerned, current empirical estimates are mainly based on measurements of nebular emission lines in low-metallicity, extragalactic HII regions (Izotov, Thuan, & Lipovetsky 1997; Olive, Steigman, & Skillman 1997). Recent He determinations present small observational errors ($\approx$ 1%), but large uncertainties between independent measurements: $Y_P = 0.234 \pm 0.003$ by Olive & Steigman (1995) against $Y_P = 0.244 \pm 0.002$ by Izotov & Thuan (1998). This evidence suggests that current He abundances are still dominated by systematic errors. In fact, Viegas, Gruenwald, & Steigman (2000) and Gruenwald, Steigman, & Viegas (2001) in two detailed investigations on the ionization correction for unseen neutral and doubly-ionized He in HII regions, found that He estimates should be reduced by 0.006 ($Y_P = 0.238 \pm 0.003$), a quantity which is a factor of 2-3 larger than typical statistical errors quoted in the literature. Moreover and even more importantly, Pistinner et al. (1999) on the basis of a new grid of stellar atmosphere models for OB stars found that the inclusion of both NLTE and metal-line blanketing effects causes an increase of the order of 40% in the ratio of He to H ionizing photons. This evidence together with uncertainties due to the occurrence of stellar winds, shocks, temperature fluctuations (Izotov, Thuan, & Lipovetsky 1997; Pistinner et al. 1999; Peimbert, Peimbert, & Luridiana 2001; Sauer, & Jedamzik 2001, and references therein) and of peculiar nebular dynamics certainly affects the He abundance estimates based on giant extragalactic HII regions. In addition it is worth mentioning that the HII regions used for determining the cosmological Helium abundance could have been somewhat polluted by the stellar yields of the pristine type II Supernovae, and in turn the empirical He abundances in these stellar systems should be corrected for self-pollution by massive stars. A plain evidence of this occurrence has been recently provided by Aloisi, Tosi, & Greggio (1999), and Östlin (2000). On the basis of deep HST optical and NICMOS data they have resolved the stellar content of I ZW 18 and found evidence that this blue compact galaxy hosts a relatively old population of asymptotic giant branch stars ($\approx$ 0.1-5 Gyr).

On the other hand, the comparison between star counts of horizontal branch (HB, central He burning phase) and red giant (RG, H shell burning phase) stars in Galactic Globular Clusters (GGCs) with the lifetimes predicted by evolutionary models, the so-called R parameter (Iben 1968), supplies upper limits to primordial He mass fraction of the order of 0.20 (Sandquist 2000; Zoccali et al. 2000). However, such estimates should be

cautiously treated (Bono et al. 1995; Cassisi et al. 1998), since they are hampered by current uncertainties on the nuclear cross-section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction (Buchmann 1996). Note that spectroscopic measurements of He abundances in low-mass population II stars are useless for constraining the primordial He content, because the He lines are either too faint (low-temperature stars) or affected by gravitational settling such as high temperature HB stars (Giannone & Rossi 1981; Moheler et al. 1999).

However, empirical and statistical errors affecting abundance determinations of primordial deuterium, ^{3}He, and lithium could be significantly larger than for He (Sasselov & Goldwirth 1995; Olive et al. 2000). Moreover, the primordial He content plays a paramount role in constraining both stellar ages and cosmic distances, since the Mass-Luminosity (M/L) relation of low and intermediate-mass stars during H and He burning phases depends on Y_P (Bono et al. 2000). At the same time, at fixed He to metal enrichment ratio the He abundance adopted to model evolutionary and pulsational properties of metal-rich stellar structures does depend on Y_P as well (Bono et al. 1997; Zoccali et al. 2000).

The physical baryon density of the universe is one of the observables that can be determined with high accuracy using measurements of CMB anisotropies at intermediate and small angular scales (see e.g., Hu et al. 2000, and references therein). It goes without saying that this observable plays a key role not only to assess the plausibility of the physical assumptions adopted in BBN models (Tegmark & Zaldarriaga 2000) but also for constraining the intrinsic accuracy of current primordial abundance estimates. According to the joint analysis of both BOOMERanG and MAXIMA-1 data, it has been estimated at 68% confidence level a baryon density $\Omega_B h^2 = 0.032^{+0.005}_{-0.004}$ (Jaffe et al. 2001). On the basis of this observable Esposito et al. (2001) found that the new CMB measurements are inconsistent at more that 3σ with both standard and degenerate BBN models.

On the other hand, the latest analysis of the BOOMERanG results, which has improved the removal of systematics from the data (Netterfield et al. 2001), found $\Omega_b h^2 = 0.022^{+0.004}_{-0.003}$ (de Bernardis et al. 2001), in very good agreement with the BBN value. The same conclusion has been derived from the analysis of the ground-based CMB observations performed by the DASI interferometer (Halverson et al. 2001), which also found $\Omega_b h^2 = 0.022^{+0.004}_{-0.003}$ (Pryke et al. 2001). This notwithstanding, the new analysis of the MAXIMA data (Lee et al. 2001), which extended the high l coverage of the power spectrum measurement, still points towards somewhat higher values of the physical baryon density: $\Omega_b h^2 = 0.032 \pm 0.006$ (Stompor et al. 2001). Finally, we mention the measurements of the CMB power spectrum at l >1000 by the Cosmic Background Imager. From these observations, and by assuming a flat cosmological model, the likelihood for the physical baryon density is found to peak at $\Omega_b h^2$=0.009 (Padin et al. 2001). Current physical baryon

densities based on CMB measurements and BBN models would imply that Y_P might range from roughly 0.24 to approximately 0.26.

The main aim of this investigation is to constrain Y_P on the basis of recent CMB measurements and two stellar observables that depend on Y_P, namely the TRGB luminosity and the ZAHB luminosity. In §2 we discuss in detail the adopted theoretical framework as well as the comparison between predicted and empirical observables. The effect of a change in Y_P abundance on the *UV-upturn* as well as on CMB anisotropies are presented in §3 and §3.1 respectively. Our conclusions and final remarks are briefly mentioned in §4.

2. Stellar constraints on Y_P

On the basis of the new CMB measurements and BBN models Esposito et al. (2000) estimated at 68% confidence level a Y_P abundance ranging from 0.249 to 0.254. However, recent investigations (Tegmark & Zaldarriaga 2000; Padin et al. 2001; Stompor et al. 2001; Tegmark, Zaldarriaga, & Hamilton 2001) suggest on the basis of CMB measurements and of the simplest flat inflation model that the baryon density should range from 0.009 to 0.045. The upper limit taken at face value would imply a larger primordial He content. As a generous but still plausible primordial He content we adopted $Y_P = 0.26$. To assess the impact that such a determination has on stellar structures we selected two observables, namely the luminosity of ZAHB stars and the luminosity of the tip of TRGB stars. The previous observables refer to stars belonging to GGCs. The reasons why we selected these observables are the following: 1) the stellar population in GGCs are among the oldest stars in the Galaxy, and therefore they are the best laboratory to investigate the primordial He content. The comparison between theory and observations in GGCs is more predictable when compared with field, halo stars, since it relies on stars that are coeval, located at the same distance, and chemically homogeneous[*]. 2) The ZAHB in GGCs marks the phase in which the stars are mainly supported by 3α reaction in the stellar center and it is a well-defined observational feature. The ZAHB luminosity depends on the He core mass and an increase of 15% in Y causes an increase in the luminosity of approximately 0.16 mag (Sweigart & Gross 1976; Raffelt 1990). 3) According to current evolutionary prescriptions the TRGB phase marks the onset of central He burning (He-core flash) in low-mass stars and its luminosity strongly depends on the He-core mass, and in turn on the initial He content. In fact, Sweigart & Gross (1978) found that an increase of 15% in

[*]Note that the initial He content in stellar populations typical of GGCs is an upper limit for Y_P, since the latter was somewhat contaminated by the debris of the first stellar generation.

Y causes a decrease in the TRGB luminosity of 0.1 mag. Finally, we mention that the previous observables are virtually unaffected by cluster age ($\approx 13 \pm 3$ Gyr; Vandenberg, Stetson, & Bolte 1996), since for stellar ages larger than $\approx$6 Gyr both the ZAHB and the TRGB luminosities do not depend on age (Castellani, Degl'Innocenti, & Luridiana 1993; Lee, Freedman, & Madore 1993; Cassisi & Salaris 1997; Salaris & Cassisi 1998).

Fig. 1 shows the comparison between predicted and observed ZAHB luminosity at the RR Lyrae effective temperature ($\log T_e = 3.85$) as a function of global metallicity[†]. The approach adopted to estimate the empirical bolometric magnitudes as well as their errors have been discussed by De Santis & Cassisi (1999). The solid and the dashed line show the ZAHB luminosities predicted by Cassisi & Salaris (1997) and by Vandenberg et al. (2000). The comparison between theory and observations suggests that HB models constructed by the previous authors are in good agreement with empirical data. On the other hand, the ZAHB luminosities predicted by HB models constructed by assuming $Y_P = 0.26$ (dotted line) are 1.5σ brighter than the observed ones. Note that current predictions on ZAHB luminosities are still controversial, since there is a mounting evidence that recent HB models based on new input physics (equation of state, neutrino energy loss rates, conductive opacities) are systematically brighter than observed and predicted by canonical HB models (Cassisi et al. 1999; Bono, Castellani, & Marconi 2000). However, such a conundrum does not affect our conclusion, because the systematic shift in the luminosity showed by He-enhanced HB models is a differential effect.

Fig. 2 shows the comparison between theory and observations for the TRGB bolometric magnitudes in a sample of 12 GGCs as a function of global metallicity. Apparent bolometric magnitudes were estimated by Frogel, Persson, & Cohen (1983) and by Ferraro et al. (2000). The distance moduli adopted to derive the absolute magnitudes were estimated by comparing predicted ZAHB luminosities at fixed chemical composition, derived by adopting the same theoretical framework, with the observed distribution of HB stars in the Color-Magnitude diagram of each individual cluster. Theoretical predictions (solid line) refer to models constructed by adopting a canonical initial He content of 0.23 and global metallicities ranging from [M/H]=-2.4 to -0.4. The top panel shows that the predicted luminosities are systematically brighter than the observed ones. This mismatch between theory and observations is expected and caused by the fact that the empirical estimates are hampered by sample size and also by the decrease in the lifetimes of the stellar structures approaching the TRGB. By taking into account the typical sample sizes of cluster RGB stars, Salaris & Cassisi (1997) found that the 30% of clusters should lay within 0.1 mag

---

[†]The global metallicity is a parameter which accounts for both iron and $\alpha - element$ abundances (Salaris et al. 1993; Vandenberg et al. 2000).

(dotted line) the predicted TRGB luminosity and the 70% within 0.3 mag (dashed line) the predicted ones. Data plotted in the top panel support, within current uncertainties, this prediction. As a matter of fact, more than 70% of the empirical TRGB bolometric magnitudes lay within the expected range (dashed and dotted lines) and only a few clusters attain magnitudes close to predicted M_{Bol}^{tip} values.

The bottom panel of Fig. 2 shows the same empirical data plotted in the top panel. Theoretical predictions on TRGB bolometric magnitudes are based on evolutionary models constructed by adopting an initial He content of 0.26. At the same time, the absolute bolometric magnitudes were estimated by adopting the distance moduli obtained by comparing observed HB stars with the ZAHB luminosities predicted by HB models constructed by adopting $Y_P = 0.26$, i.e. the same He content adopted in He enhanced models of Fig. 1. A glance at the data plotted in this panel shows that more than 70% of the clusters in our sample attain bolometric magnitudes similar or even brighter than predicted by He enhanced models. This finding is at odds with the straightforward statistical arguments mentioned above, and indeed only two measurements lay within 0.3 mag from the predicted TRGB bolometric magnitudes.

3. The dependence of the *UV-upturn* on Y_P

Stellar observables discussed in the previous section can be extended over Local Group (LG) galaxies or slightly beyond, i.e. on scales of the order of a few Mpc. Moreover, current He estimates are based on spectroscopic measurements of HII regions in extremely metal-poor blue compact galaxies. These systems are located outside the LG and their typical distances are, within the uncertainties, of the order of 200-300 Mpc. This means that previous stellar observables and HII regions can hardly be adopted on Gpc scale even by using the largest telescopes. However, the He abundance on these scales can be probed on the basis of the *UV-upturn*. This phenomenon shows up as a sharp rise in the spectra of elliptical and S0 galaxies for wavelengths smaller than 2500 $\AA$. According to both theoretical (Greggio & Renzini 1990; Castellani & Tornambè 1991; Castellani et al. 1994) and empirical (Burstein et al. 1988; Brown et al. 2000) evidence the *UV-upturn* is driven by the progeny of extreme and hot HB stars, namely AGB-manquè and post-early-AGB (Castellani & Tornambè 1991). This observable presents a strong dependence on age, since He abundance affects the mass of main sequence turn off stars, the HB morphology, and in turn the UV emission of old stellar populations. As a consequence, the *UV-upturn* is a powerful age indicator in elliptical galaxies (Tantalo et al. 1996; Greggio & Renzini 1999).

However, as already mentioned in the previous section the evolutionary properties of

HB stars do depend on the primordial He content. In particular, an increase in Y causes, at fixed age, an increase in the ZAHB luminosity‡. Current HB evolutionary models for metal-poor and metal-rich structures ($0.0001 \leq Z \leq 0.02$) constructed (Zoccali et al. 2000) by adopting different He contents ($0.20 \leq Y_P \leq 0.26$) suggest that the HB luminosity at $\log T_e = 3.85$ scales with the initial He content according to the following relation: $\Delta \log L_{HB}/\Delta Y \approx 1.8$. A quite similar value was also suggested by Raffelt (1990) on the basis of HB models computed by Sweigart & Gross (1976, 1978). Thus suggesting that evolutionary predictions on this ratio are quite robust. This means that in metal-rich populations, which is typical of E and S0 galaxies, an increase in Y of a factor of two (0.23 vs 0.46) causes an increase in $\log L_{HB}$ of the order of 0.40 dex.

This result is a rough estimate of the impact of Y on the HB luminosity, it cannot be easily extrapolated to the *UV-upturn*. In fact, the crucial parameters for this phenomenon are the changes in HB and post-HB evolutionary lifetimes as well as the UV flux and not the bolometric one. This means that a detailed quantitative estimate does require synthetic models which simultaneously account for both H and He burning phases, and in turn for the change in the spectral energy distribution (SED) of the entire field population (Brown et al. 1998). This notwithstanding, we are interested in estimating the dependence of the *UV-upturn* on He content at intermediate redshifts, and therefore we constructed four metal-poor (Z=0.0001) extreme HB structures at different He contents, namely 0.15, 0.23, 0.35, and 0.5 (see Fig. 3). The He-core masses of these structures were estimated by constructing H-burning evolutionary tracks that reach the RGB tip with an age of ≈ 10 Gyr. We find that the He-core masses for the previous compositions are 0.523, 0.511, 0.481, and 0.433 $M_\odot$ respectively. To estimate the impact of He content on the UV emission of AGB-manquè stars we selected a typical effective temperature for these structures, namely $\log T_e \approx 4.45$. One finds that the total mass of HB structures at the selected compositions range from $M/M_\odot = 0.53$ ($Y_P = 0.15$) to 0.45 ($Y_P = 0.50$). The evolution was followed from central He-burning till the beginning of the white dwarf cooling sequence (see Fig. 3), and then we estimated the total spectral energy distribution (SED) for the four structures according to the individual evolutionary lifetimes. It turns out that the UV emission of Extreme Horizontal Branch (EHB) structures is relatively sensitive to the He content, and indeed an increase from $Y_P = 0.23$ to $Y_P = 0.35$ and $Y_P = 0.50$ causes a decrease in the UV emission by roughly 10% and 22% respectively. At the same time, a decrease from

‡Note that the ZAHB luminosity is governed by the size of the He-core and by He abundance in the envelope. However, the ZAHB luminosity of hot HB stars mainly depends on the He-core mass due to the marginal efficiency of the H-burning shell. Therefore, an increase in the initial He abundance causes a decrease in the He-core mass at the He-flash, and in turn a decrease in the luminosity of hot HB stars.

$Y_P = 0.23$ to $Y_P = 0.15$ causes an increase by ≈9%. This effect is due to the fact that among EHB structures an increase in Y causes, at fixed age and effective temperature, a decrease in the He-core mass and in turn in the ZAHB luminosity. This means that He-rich EHB structures spend a substantial portion of their central He-burning lifetime at lower luminosities. Therefore their total UV emission decreases when compared with He-poor structures. Moreover, we also find that an increase in the He content causes in metal-poor structures a decrease in the range of stellar masses evolving at high temperatures during He-burning. In fact, we find that the largest mass that evolve as AGB-manquè slightly decreases from 0.54 at $Y_P = 0.15$ to 0.52 at $Y_P = 0.35$. This finding further strengthens the evidence that in metal-poor structure an increase in the He abundance causes a decrease in the UV emission. Note that such a trend is at odds with the behavior in metal-rich structure, and indeed Dorman et al. (1993) found that an increase in Y causes an increase in the largest mass evolving as AGB-manquè, and in turn in the UV emission. The difference seems to be due to the fact that the evolution of metal-poor EHB structures is mainly governed by central He burning, and therefore by the He-core mass at the tip of the RGB. On the contrary the H-burning shell is more efficient in metal-rich EHB structures. This means that the He-core mass in these structures undergoes a mild increase during the central He burning phase, and therefore the range of stellar masses evolving as AGB-manquè increases as well. Once again we note that current arguments are preliminary but plausible speculations of the impact of He-content on the *UV-upturn*. However, a firm quantitative evaluation requires the calculation of synthetic population models that account for both AGB-Manquè and post-early-AGB structures.

This seems a promising result, since a substantial increase/decrease in the He content should cause, at fixed look-back time and similar star formation histories, a decrease/increase in the scatter of the empirical average restframe 1550-V colors, i.e. the fingerprint of the *UV-upturn*. Moreover and even more importantly, present-day instrumentation allowed the detection and measurement of the *UV-upturn* in intermediate redshift ($z \approx 0.6$) E galaxies (Brown et al. 2000b). By assuming a Hubble constant $H_0 = 67$ km s^{-1} Mpc^{-1} and an Eistein-de Sitter cosmological model one finds that the comoving distance D_M and the look-back time t_l of this E galaxy are ≈ 1.8 Gpc and ≈ 5 Gyr respectively. On the other hand, if we assume a high lambda cosmological model ($\Omega_M = 0.2$ $\Omega_\lambda = 0.8$) one finds $D_M \approx 2.2$ Gpc and $t_l \approx 6$ Gyr. This is the reason why we constructed EHB structures by adopting He-core masses at evolutionary ages of approximately 10 Gyr. Therefore this evidence and our finding seem to support the use of the *UV-upturn* to trace the He content up to Gpc scales.

3.1. The dependence of the CMB on Y_P

As it has been emphasized countless times in the literature (see e.g., Jungman et al. 1996; Hu & White 1996; Kamionkowski & Kosowsky 1999), observations of CMB anisotropies provide a powerful way of setting tight constraints on the value of most cosmological parameters. In particular, the angular power spectrum of CMB temperature fluctuations depends both on the primordial fluctuations which seeded structure formation in the universe and on the physical processes occurring before the recombination in the baryon-photon plasma. Within the framework of inflationary adiabatic models, these processes leave a characteristic imprint in the angular power spectrum in the form of a series of harmonic peaks (usually named "acoustic peaks" in the literature) whose height and position is sensitively dependent on the parameters of the cosmological model.

While the parameter which is most robustly determined from measurements of the CMB power spectrum is undoubtedly the total energy density of the universe, many other parameters are measurable with striking precision. Among them, the physical density of baryonic matter in the universe, whose value affects the height ratio of odd and even peaks in the spectrum: in particular, a high baryon density enhances the height of the first peak with respect to the second, and vice-versa. This effect is quite relevant even for small variations of $\Omega_b h^2$, as shown in Fig. 4. The dependence of the CMB anisotropy on the primordial He mass fraction is, on the contrary, quite weak. As shown in Figure 5, the effect on the first peak is just about 3%, even for an unrealistically large range of values $0.15 \lesssim Y_P \lesssim 0.50$. One has to go beyond the second peak in order to obtain effects larger than 10% . We stress the fact that the effect of both the baryon density and the primordial He abundance on the CMB pattern is only relevant at small angular scales (corresponding to $l \gtrsim 100$ in the power spectrum). These scales are only weakly affected by the uncertainty deriving from the limited coverage of the observed region, and from the so called "cosmic variance" resulting from the fact that we can only observe one statistical realization (our sky) drawn from the underlying cosmological model. On the other hand, the high l end of the spectrum is unfortunately the one which is currently most at risk of being affected by unknown systematics such as pointing inaccuracies, poorly known beam pattern, residual instrumental noise, etc.

Until recent times, no high resolution observation of the CMB anisotropy pattern was available. Consequently, the structure of peaks in the power spectrum could not be resolved with the accuracy needed to obtain a precise measurement of the baryon density. The situation has dramatically changed after recent observations. The MAXIMA and BOOMERanG experiments (Hanany et al. 2000; de Bernardis et al. 2000) produced the first high-resolution maps of the CMB, and measured the CMB angular power spectrum

on a wide range of l: $36 \lesssim l \lesssim 1200$, corresponding to angular scales $10' \lesssim \theta \lesssim 10°$. This has provided tight constraints on the main parameters of the inflationary adiabatic model (Balbi et al. 2000; Lange et al. 2000; Jaffe et al. 2001). In particular, the constraints on the physical baryon density from the joint analysis of the MAXIMA and BOOMERanG data, $\Omega_B h^2 = 0.032^{+0.005}_{-0.004}$, was found to be higher than the one derived from primordial nucleosynthesis considerations $\Omega_b h^2 = 0.020 \pm 0.002$ (see e.g., Burles, Nollett & Turner 2001a; Burles et al. 1999) although the BBN value fall within the CMB 95% confidence interval. This stirred some discussion about the existence of a conflict between CMB and BBN and possible explanation for it (for example, Burles, Nollett & Turner 2001b; Kurki-Suonio & Sihvola 2001; Esposito et al. 2001; Di Bari & Foot 2001; Lesgourgues & Peloso 2000). It is remarkable, however, that these first limits from the CMB agree, within 2σ, with those from the BBN, which are derived using a different set of measurements.

4. Summary and final remarks

Recent measurements of the CMB anisotropy provided the unique opportunity to evaluate several fundamental cosmological parameters and to supply for all of them a preliminary but plausible estimate of their error budget. The impact of these new measurements on cosmological models uncorked a flourishing literature. However, it is not easy to assess on a quantitative basis to what extent current differences in the physical baryon density derived from CMB observations are caused by deceptive systematic errors. As a matter of fact, CMB measurements of $\Omega_b h^2$ range from 0.009 (Padin et al. 2001) to 0.032 ± 0.012 (95% confidence level, Stompor et al. 2001). According to BBN models the new measurements imply that Y_P might range from approximately 0.24 to roughly 0.26. By adopting the upper limit on Y_P we investigated the impact of the change on two stellar observables, namely the ZAHB luminosity and the luminosity of the tip of the RGB. The main outcome of our analysis is that an increase in the primordial He content from the canonical $Y_P = 0.23$ to $Y_P = 0.26$ does not seem to be supported by the comparison between current theoretical predictions and empirical data.

We found that the *UV-upturn* can be adopted to estimate the primordial He content. In fact, numerical experiments suggest that an increase of Y_P from 0.23 to 0.50 causes a decrease in the UV emission at least of the order of 20%. This is a preliminary rough estimate based on the assumption that AGB-manquè structures are the main sources of the *UV-upturn*. An interesting feature of this observable is that current instruments can allow us to measure the *UV-upturn* up to distances of the order of Gpcs. Note that to supply quantitative estimates of Y_P on the basis of the comparison between synthetic and observed

UV-upturns it is necessary to account for the SED typical of complex stellar populations as a function of redshift (Tantalo et al. 1996; Yi et al. 1999). However, theoretical predictions should be cautiously treated, since UV flux when moving from low to high metal contents strongly depends on the efficiency of the mass loss as well as on the He to metal enrichment ratio (Greggio & Renzini 1999). The scenario has been further complicated by recent spectroscopic measurements of hot HB stars ($T_e \geq 10,000$ K) in metal-poor GGCs (M15, M13). In fact, Behr et al. (2000) and Behr, Cohen, & McCarthy (2000) found that in these stars the iron abundance is enhanced by 1-2 order of magnitudes, whereas the He content is depleted by at least one order of magnitude respect to solar abundance. Unfortunately, we still lack quantitative estimates of the impact that such a peculiarities have on the UV emission.

Theoretical and empirical arguments support the evidence that the density of baryons in the universe is homogeneous (Copi, Olive, & Schramm 1995). The same outcome applies to large scale chemical inhomogeneities (Copi, Olive, & Schramm 1996). However, it has been recently suggested by Dolgov & Pagel (1999, hereinafter DP) a new cosmological model that predicts a substantial spatial variation in the primordial chemical composition and a small baryon density variation. This investigation was triggered by a difference of one order of magnitude in the deuterium abundance of damped $Ly\alpha$ systems along the line of sight of high-redshift ($0.5 \leq z \leq 3.5$) QSOs (D'Odorico et al. 2001; Steigman et al. 2001). The scenario developed by DP relies on a model of leptogenesis (Dolgov 1992) in which takes place a large lepton asymmetry and this asymmetry undergoes strong changes on spatial scales ranging from Mega to Giga pcs. The key feature of this model is to predict a large and varying lepton asymmetry and a small baryon asymmetry. Within this theoretical framework the He mass fraction in deuterium-rich regions should range from 35% to 60%, while the Li one should increase up to 10^{-9}, while the variation of the photon temperature should be $\delta T/T \approx 2.5 \times 10^{-3}$. Obviously, the hypothesis that current changes in baryon density are due to real spatial variations is premature as any further speculative issue. Future full-sky CMB observations from space missions such as NASA's MAP (Wright 1999) and ESA's PLANCK (Mandolesi et al. 1998) will play a crucial role to properly address the problem of the spatial variation, since they will supply a larger sensitivity up to very high l ($l > 1000$) and an improved control on systematics.

We warmly thank Claudia Maraston for kindly providing us the spectral energy distribution of current HB models. We also ackowledge an anonymous referee for his/her useful suggestions that improved the readability of the paper. This work was supported by MURST/Cofin2000 under the project: "Stellar Observables of Cosmological Relevance" (G. B., R. B., & S. C.).

REFERENCES

Aloisi, A., Tosi, M., & Greggio, L. 1999, AJ, 118, 302

Balbi, A., et al., 2000, ApJL, 545, L1

Behr, B. B., Cohen, J. G., McCarthy, J. K. 2000, ApJ, 531, L37

Behr, B. B., Djorgovski, S. G., Cohen, J. G., McCarthy, J. K., Cotè, P., Piotto, G., Zoccali, M. 2000, ApJ, 528, 849

Bono, G., Caputo, F., Cassisi, S., Incerpi, R., & Marconi, M. 1997, ApJ, 483, 811

Bono, G., Caputo, F., Cassisi, S., Marconi, M., Piersanti, L., & Tornambé, A. 2000, ApJ, 543, 955

Bono, G., Castellani, V., Degl'Innocenti, S., & Pulone, L. 1995, A&A, 297, 115

Bono, G., Castellani, V., & Marconi, M. 2000, ApJ, 532, L129

Brown, T. M., Bowers, C. W., Kimble, R. A., Sweigart, A. V., & Ferguson, H. C. 2000, ApJ, 532, 308

Brown, T. M., Ferguson, H. C., Stanford, S. A., & Deharveng, J.-M. 1998, ApJ, 504, 113

Burles, S., Nollett, K.M., & Turner, M. 2001a, ApJL, 552, L1

Burles, S., Nollett, K.M., & Turner, M. 2001b, Phys. Rev. D, 63, 063512

Burles, S., et al., 1999, Phys. Rev. Lett., 82, 4176

Burstein, D., Bertola, F., Buson, L. M., Faber, S. M., & Lauer, T. R. 1988, ApJ, 328, 440

Cassisi, S., Castellani, V., Degl'Innocenti, S., & Weiss, A. 1998, A&AS, 129, 267

Cassisi, S., Castellani, V., Degl'Innocenti, S., Salaris, M., & Weiss, A. 1999, A&AS, 134, 103

Cassisi, S., & Salaris, M. 1997, MNRAS, 285, 593

Castellani, M., Castellani, V., Pulone, L., & Tornambé, A. 1994, A&A, 282, 711

Castellani, V., Degl'Innocenti, S., & Luridiana, V. 1993, A&A, 272, 442

Castellani, M., & Tornambé, A. 1991, ApJ, 381, 393

Copi, C. J., Olive, K. A., & Schramm, D. N. 1995, ApJ, 451, 51

Copi, C. J., Olive, K. A., & Schramm, D. N. 1996, astro-ph/9606156

de Bernardis, P., et al. 2000, Nature, 404, 955

de Bernardis, P., et al. 2001, ApJ, submitted, astro-ph/0105296

De Santis, R., & Cassisi, S. 1999, MNRAS, 308, 97

Di Bari, P. & Foot, R. 2001, Phys. Rev. D, 63, 043008

D'Odorico, S., Dessauges-Zavadsky, M., & Molaro, P. 2001, A&A, 368, L21

Dorman, B., Rood, R. T., & O'Connell, R. W. 1993, ApJ, 419, 596

Dolgov, A. D. 1992, Phys. Rep., 222, 6

Dolgov, A. D., & Pagel, B. E. J. 1999, NewA, 4, 223 (DP)

Esposito, S., et al., 2001, Phys. Rev. D, 63, 043004

Ferraro, F. R., Montegriffo, P., Origlia, L., & Fusi Pecci, F. 2000, AJ, 119, 1282

Frogel, J. A., Persson, S. E., & Cohen, J. G. 1983, ApJS, 53, 713

Giannone, P., & Rossi, L. 1981, A&A, 102, 386

Greggio, L., & Renzini, A. 1990, ApJ, 364, 35

Greggio, L., & Renzini, A. 1999, Mem. Soc. Astr. It., 70, 691

Gruenwald, R., Steigman, G. & Viegas, S. M. 2000, ApJ, accepted, astro-ph/0109071

Halverson, N.W. et al. 2001, ApJ, submitted, astro-ph/0104489

Hanany, S., et al., 2000, ApJL, 545, L5

Hu, W. & White, M. 1996, ApJ, 471, 30

Iben, I. Jr. 1968, Nature, 220, 143

Izotov, Y. I., & Thuan, T. X. 1998, ApJ, 497, 227

Izotov, Y. I., Thuan, T. X., & Lipovetsky, V. A. 1997, ApJS, 108, 1

Jaffe, A., et al. 2001, Phys. Rev. Lett. 86, 3475

Jungman, G., et al. 1996, Phys.Rev. D54, 1332

Kamionkowski, M. & Kosowsky, A. 1999, Ann.Rev.Nucl.Part.Sci. 49, 77-123

Kurki-Suonio, H. & Sihvola, E., 2001, Phys. Rev. D, 63, 083508

Lange, A. et al., 2001, Phys. Rev. D, 63, 042001

Lesgourgues, J. & Peloso, M. 2000, Phys. Rev. D, 62, 081301

Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, ApJ, 417, 533

Lee, A.T., et al. 2001, ApJ, 561, L1

Mandolesi, N., et al. 1998, Planck Low Frequency Instrument, a proposal submitted to ESA

Moehler, S., Sweigart, A. V., Landsman, W. B., Heber, U., & Catelan, M. 1999, A&A, 346, L1

Netterfield, B., et al. 2001, ApJ, submitted, astro-ph/0104460

Olive, K. A., & Steigman, G. 1995, ApJS, 97, 49

Olive, K. A., Steigman, G., & Skillman, E. D. 1997, ApJ, 483, 788

Olive, K. A., Steigman, G., & Walker, T. P. 2000, Phys. Rep., 333, 389

Östlin, G. 2000, ApJ, 535, L99

Padin, S., et al. 2001, ApJ, 549, L1

Peimbert, M., Peimbert, A., & Luridiana, V. 2001, ApJ, accepted, astro-ph/0107189

Pistinner, S. L., Hauschildt, P. H., Eichler, D., & Baron, E. A. 1999, MNRAS, 302, 684

Pryke, C., et al., 2001, ApJ, submitted, astro-ph/0104490

Puget, J. L., et al. 1998, PLANCK High Frequency Instrument, a proposal submitted to ESA

Raffelt, G. G. 1990, ApJ, 365, 559

Salaris, M., & Cassisi, S. 1997, MNRAS, 289, 406

Salaris, M., & Cassisi, S. 1998, MNRAS, 298, 166

Salaris, M., Chieffi, A., & Straniero, O. 1993, ApJ, 414, 580

Sandquist, E. L. 2000, MNRAS, 313, 571

Sasselov, D., & Goldwirth, D. 1995, ApJ, 444, L5

Sauer, D., & Jedamzik, K. 2001, A&A, submitted, astro-ph/0104392

Stompor, R. et al. 2001, ApJ, 561, L7

Sweigart, A. V., & Gross, P. G. 1976, ApJS, 32, 367

Sweigart, A. V., & Gross, P. G. 1978, ApJS, 36, 405

Tantalo, R., Chiosi, C., Bressan, A., & Fagotto, F. 1996, A&A, 311, 361

Tegmark, M., & Zaldarriaga, M. 2000, ApJ, 544, 30

Tegmark, M., Zaldarriaga, M., & Hamilton A. J. S. 2001, Phys. Rev. D., 63, 043007

Vandenberg, D. A., Stetson, P. B., & Bolte, M. 1996, ARA&A, 34, 461

VandenBerg, D. A., Swenson, F. J., Rogers, F. J.,, Iglesias, C. A., & Alexander, D. R. 2000, ApJ, 532, 430

Viegas, S. M., Gruenwald, R., & Steigman, G. 2000, ApJ, 531, 813

Wright, E.L., 1999, New Astr.Rev., 43, 257

Yi, S., Lee, Y.-W., Woo, J.-H., Park, J.-H., Demarque, P., Oemler, A. Jr. 1999, ApJ, 513, 128

Zoccali, M., Cassisi, S., Piotto G., Bono G., & Salaris M. 1999, ApJ, 518, L49

Zoccali, M., Cassisi, S., Bono, G., Piotto, G., Rich, R. M., & Djorgovski, S. G. 2000, ApJ, 538, 289

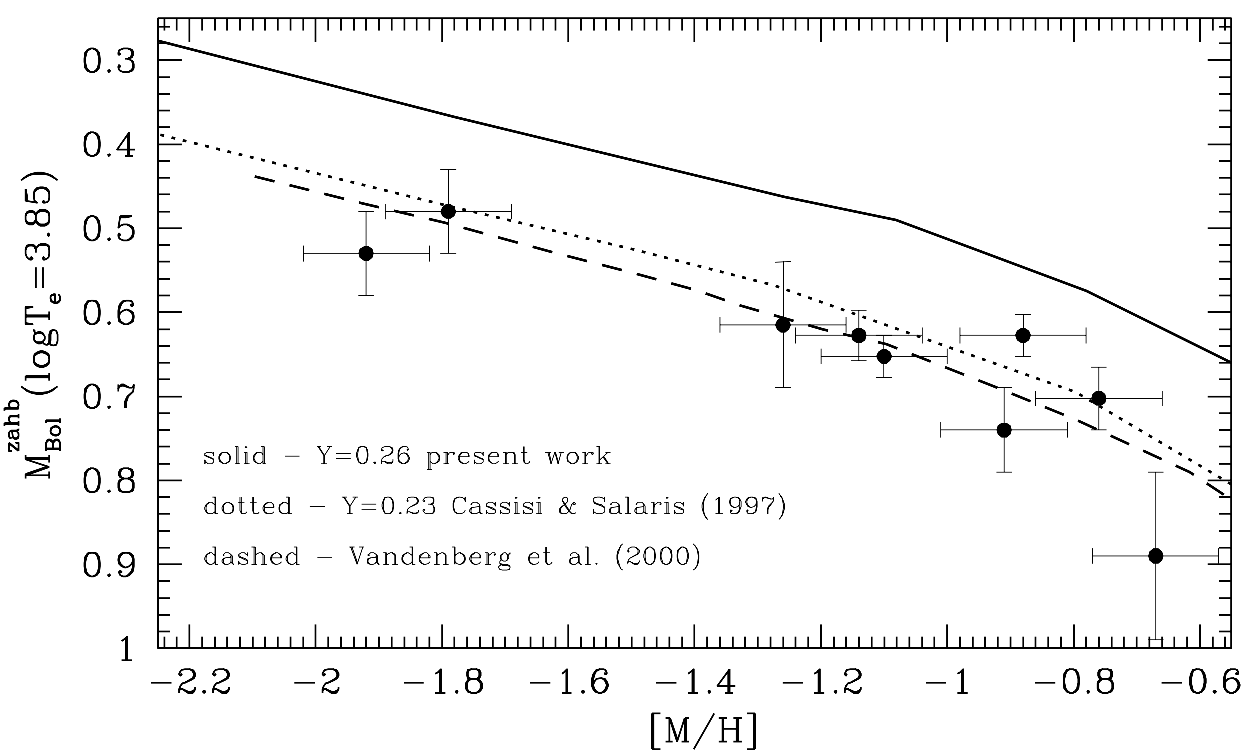
Fig. 1.— Bolometric magnitude of the Zero Age Horizontal Branch at the effective temperature of RR Lyrae stars ($\log T_e = 3.85$) as a function of the global metallicity. Dotted and dashed lines show current theoretical predictions based on a primordial He content $Y_P = 0.23$, while the solid line for $Y_P = 0.26$. The latter is at odds with empirical estimates.

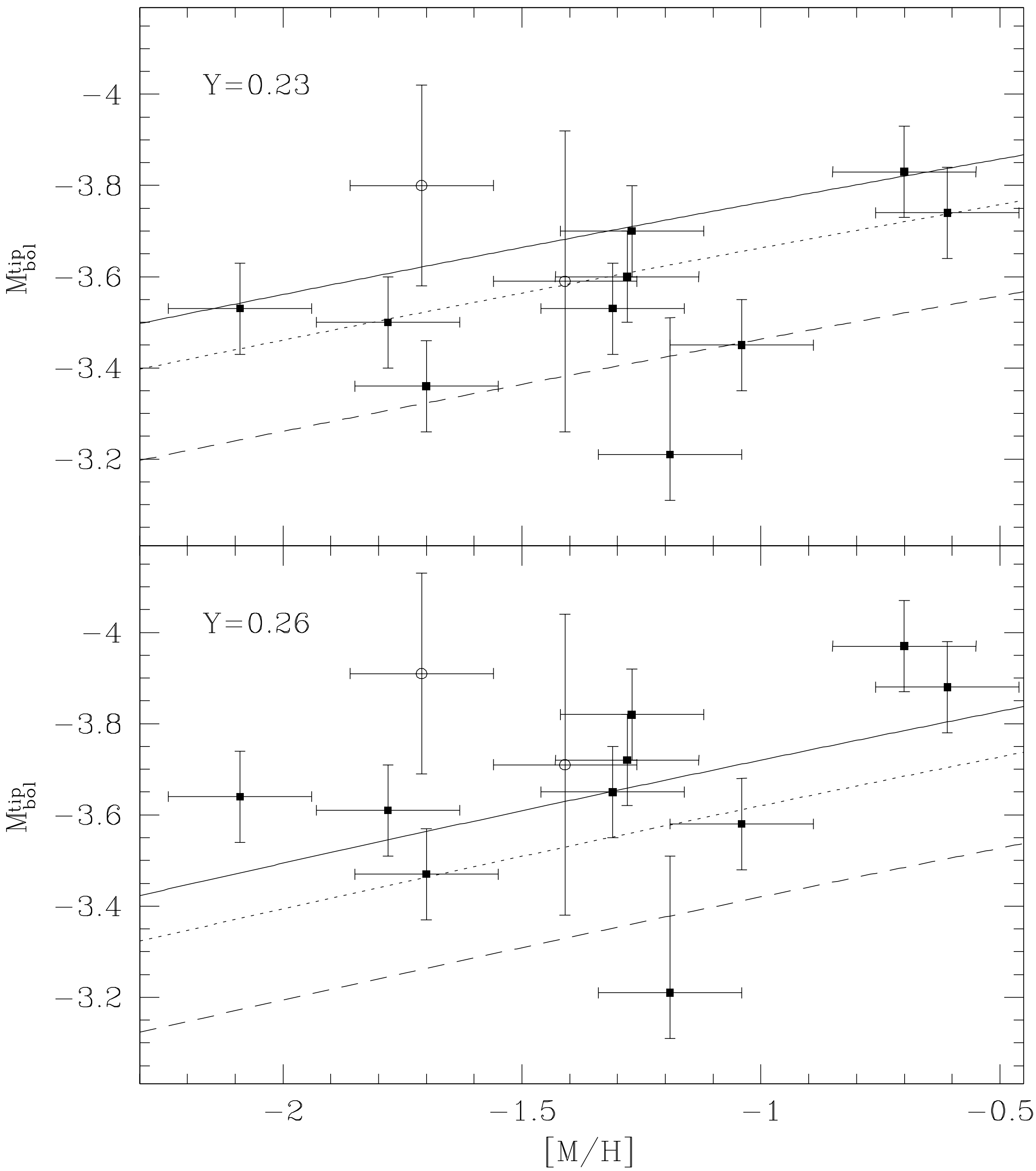
Fig. 2.— Top panel: comparison between predicted (solid line) and empirical bolometric magnitude for the tip of the Red Giant Branch. To account for the typical sample size, the dotted and the dashed lines show the luminosity range within which should lay the 30% and the 70% of empirical tip luminosities. Squares refer to data collected by Frogel et al. (1983, filled) and by Ferraro et al. (2000, open). Bottom panel: same as the top panel but for $Y_P = 0.26$.

Fig. 3.— HR diagram for metal-poor (Z=0.0001) extreme HB models at different He contents, namely 0.15, 0.23, 0.35, and 0.50. The solid line shows the ZAHB for $Y_P = 0.23$. The He-core masses were estimated by evolving H-burning structures that reach the RGB tip with an age of approximately 10 Gyr. The total ZAHB masses (see labeled values) were selected to populate an effective temperature -$\log T_e \approx 4.45$- typical of AGB-Manquè structures. Empty circles mark steps in age of t=25 Myr during central He-burning, while diamonds mark steps in age of t=1.5 Myr during off-ZAHB evolution (double-shell burning).

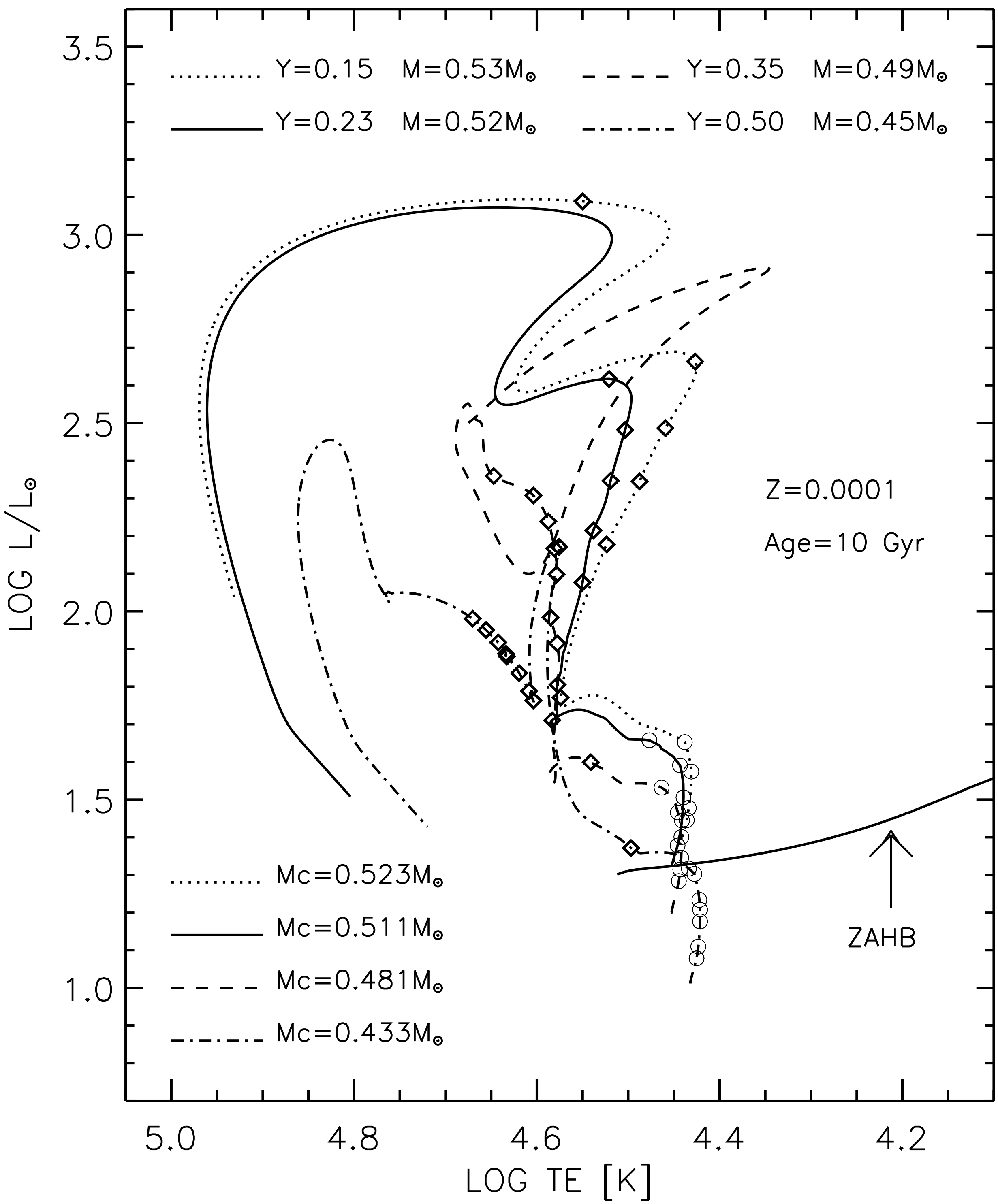
Fig. 4.— The dependence of the CMB angular power spectrum on the physical baryon density $\Omega_b h^2$. The solid line was computed assuming a value $\Omega_b h^2 = 0.02$, as derived from BBN considerations. The dashed line assumes a slightly higher value $\Omega_b h^2 = 0.03$, as preferred by the first analyses of the MAXIMA and BOOMERanG CMB data. Both spectra were computed assuming an inflationary adiabatic model, with scale invariant primordial perturbation, and with $\Omega = 1$, $\Lambda = 0.7$, $h = 0.68$ and a primordial He mass fraction $Y_P = 0.24$.

Fig. 5.— The dependence of the CMB angular power spectrum on the primordial He content. The solid line was computed using a "standard" value of $Y_P = 0.24$. The dashed line assumes $Y_P = 0.15$, while the dotted line has $Y_P = 0.50$. All spectra were computed assuming an inflationary adiabatic model, with scale invariant primordial perturbation, and with $\Omega = 1$, $\Omega_b h^2 = 0.02$, $\Omega_{CDM} h^2 = 0.12$, $\Lambda = 0.7$, $h = 0.68$.

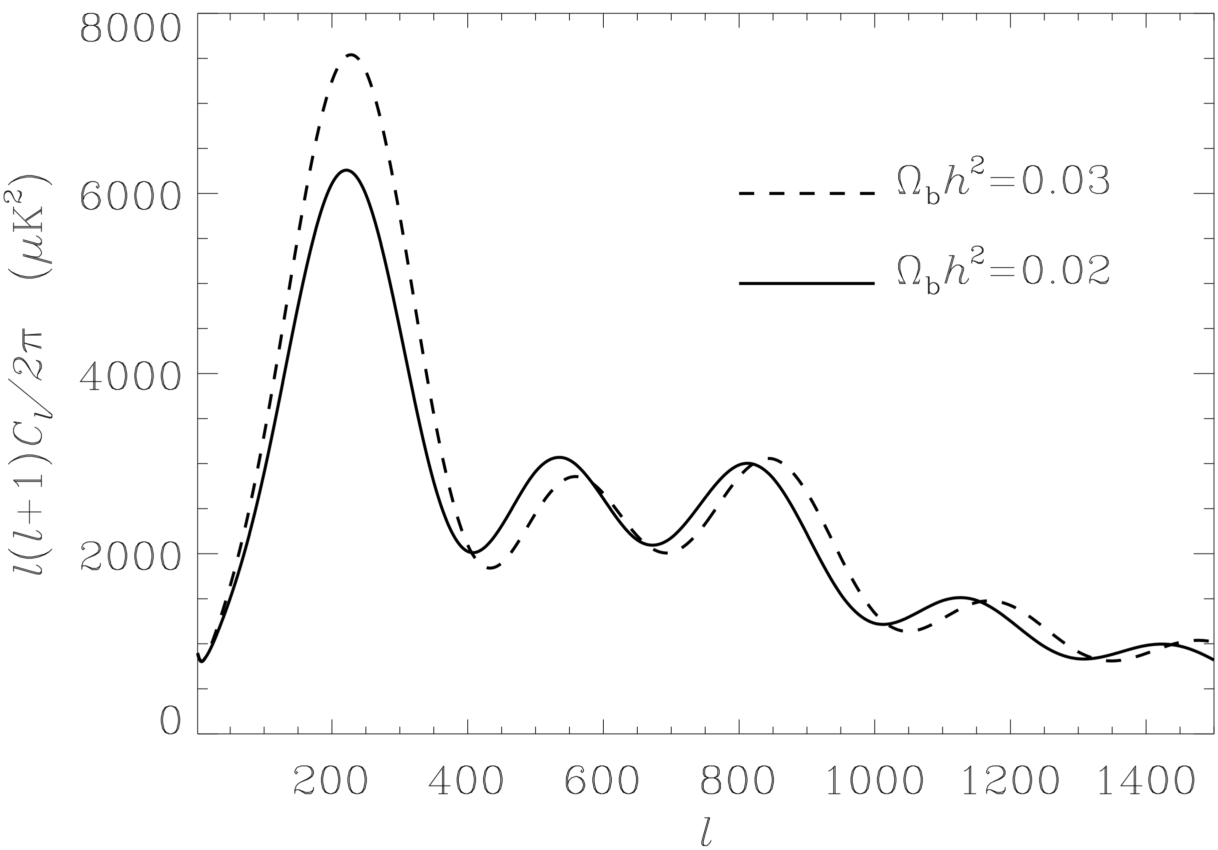

solid – Y=0.26 present work
dotted – Y=0.23 Cassisi & Salaris (1997)
dashed – Vandenberg et al. (2000)
$M_{Bol}^{zahb}(\log T_e=3.85)$
[M/H]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
−2.2
−2
−1.8
−1.6
−1.4
−1.2
−1
−0.8
−0.6



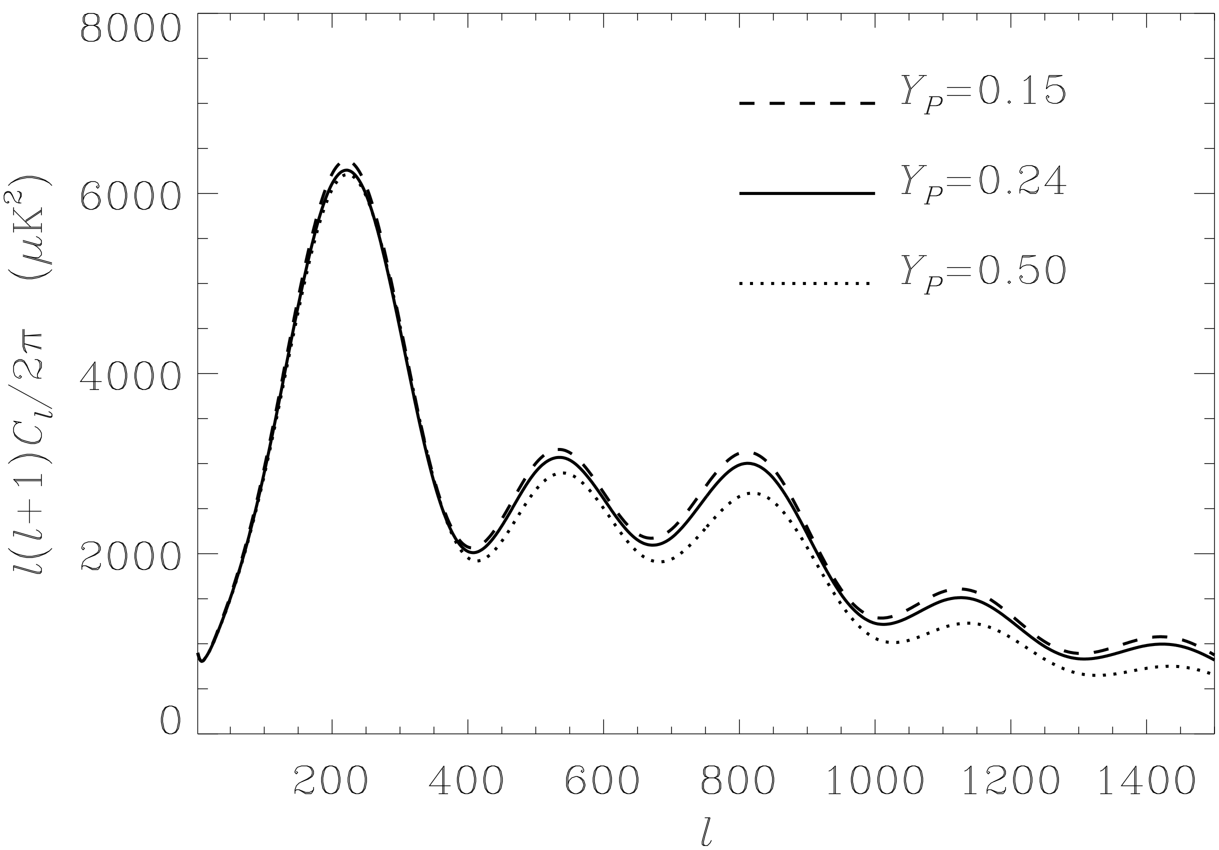
Y=0.23
Y=0.26
M_{bol}^{tip}
−4
−3.8
−3.6
−3.4
−3.2
−2
−1.5
−1
−0.5
[M/H]



Y=0.15 M=0.53M⊙
Y=0.35 M=0.49M⊙
Y=0.23 M=0.52M⊙
Y=0.50 M=0.45M⊙
Z=0.0001
Age=10 Gyr
Mc=0.523M⊙
Mc=0.511M⊙
Mc=0.481M⊙
Mc=0.433M⊙
ZAHB
LOG L/L⊙
LOG TE [K]
3.5
3.0
2.5
2.0
1.5
1.0
5.0
4.8
4.6
4.4
4.2



8000
6000
4000
2000
0
200
400
600
800
1000
1200
1400
l
$l(l+1)C_l/2\pi \quad (\mu K^2)$
$\Omega_b h^2=0.03$
$\Omega_b h^2=0.02$



Y_P=0.15
Y_P=0.24
Y_P=0.50
8000
6000
4000
2000
0
200
400
600
800
1000
1200
1400
l
$l(l+1)C_l/2\pi$ (μK^2)